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A Method To Simulate Structural Properties Of Cellular Materials For Machining Processes

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Abstract

The application of cellular metals and metal foams is still at the beginning of its development. The evaluation of the surface quality of these materials after machining processes is thus important for implementation in the field of construction. The existing tactile measurements are only capable of indicating both the structure of the material and the influences of machining processes to a limited degree.

It is therefore necessary to analyse the structure of materials and to simulate surface parameters analogously to the known parameters of the measuring technology, before a measurement system can be applied.

This work presents a method with which to analyse cross-sectional images acquired from computer tomography data as well as specially prepared cellular metal structures.

Specialised software enables analysis of these cross-sections and makes statements about the material structures and the influence that mechanical processing has on them. It also facilitates the generation of virtual surface profiles which are essential in comparative studies of the measured surface profiles of machined material.

The study will also reveal further analysis options made possible by the software. This includes the possibility of determining the density of analysed material by means of the cross-sections – in other words, a homogeneity analysis of the material structure.

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Keywords: Machining; Milling; Cellular Metal; Metal Foam; Surface Quality; Profile Method

1. Introduction

The surface quality that can be obtained with metal cutting is regarded as the most important aspect of machinability, since one may directly deduce product quality from it.

A variety of techniques can be used for evaluation, but mechanical (tactile) and optical methods are standard and have been proven effective. The parameters deduced from the measuring techniques have also established themselves and have been widely introduced into international standards.

The surface parameters of tactile metrology - such as R_a, R_z or the Abbott-Firestone curve - are widely used in mechanical engineering applications, albeit mostly confined to homogeneous materials. When evaluating heterogeneous materials, these established techniques and their corresponding measuring methods or instruments are limited. These limits result from delaminations in the case of fibre-reinforced materials or material skips in wooden materials. Cellular metallic materials are also characterized by a heterogeneous structure (Figure 1).

It is very difficult to evaluate the surface or indeed the entire material structure since the structure may include many discontinuities. For this reason, we find very few notes or statements in literature about the surface parameters measured [1]. Where these notes do exist, they are mostly just general statements [2]. One method of structure assessment is computer tomography. However, this is only suitable for a limited sample size and demands great deal of metrology and analysis effort.

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What follows is the description of a method with which one may determine surface parameters analogously to the known parameters of the measuring of cut techniques for cellular metallic materials that are generated from material separating cuts.

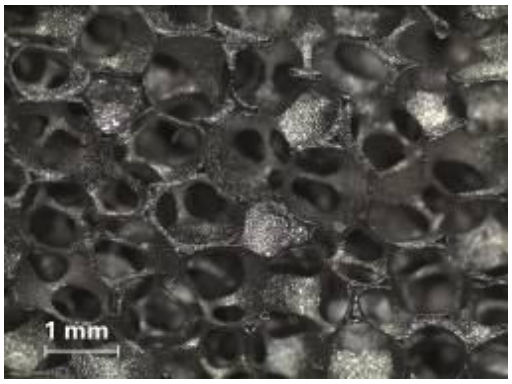

Fig. 1 Surface of a cellular steel structure with 45 ppi

2. Generation of a Cross-section Representation

Plane cross-sections of foamed metals are an initial point for the investigation of the topography. It is possible to generate these cross-sections by using for instance, computer tomography [3] or by preparing metallographic micro sections. Other techniques based on optical technologies - such as the existing methods of digital fringe projection or confocal microscopy techniques - would also be possible. The result of this should be a representation that is characterised in the separation plane purely by material and residual ratios. Since the material is distributed stochastically in the cross-section, as can be seen in the Figure 2, it is necessary to have a large cross-section for the calculation of the surface profile and other characteristics in order to obtain highly accurate calculations. For this reason, the use of metallographic micro-sections which are illustrated in the chapters below could provide a solution.

To make use of use of metallographic micro-sections, it is necessary to fill the interspaces with polymers or epoxy resins when using foamed metals. For the investigations detailed in this paper, an open-cell foamed metal was used, since its structure is suitable for interbedding. One may also fill closed-cell structures into a pre-machined cross-section and finish it.

The epoxy resin for filling in was also coloured in order to guarantee a strong contrast against the material structure. In addition, the cross-section, which is the origin for simulation, was polished. For further processing via EDP, this cross-section must then be scanned (Figure 2) by means of image scanners or microscopes and filtered (Figure 3). Using two-dimensional pixel graphs in bitmap (*.bmp) format, it is possible to precisely evaluate these sections, since this file format provides the exact RGB colour information and the position of a pixel.

In this way, a data format that is a matrix (due to its mathematical representation) is made available. The product of the columns and lines corresponds to the number of pixels of the bitmap format, while the components of the matrix include the RGB colour information. Further processing is based on the transfer of RGB colour information into a binary data format in the form of a binary image.

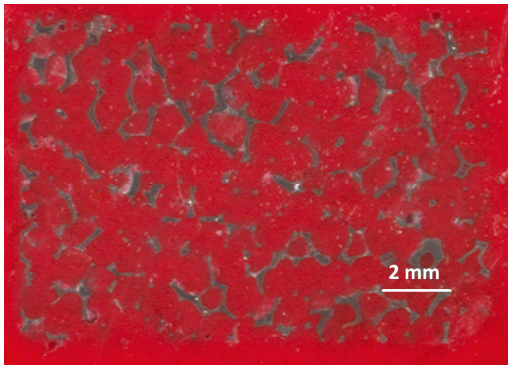

Fig. 2 Cross-section of a scanned surface

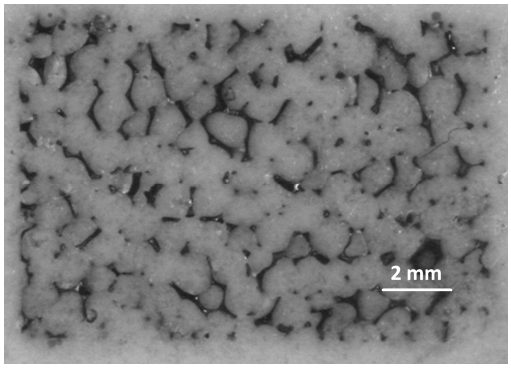

Fig. 3 Cross-section of a filtered surface

During this process, all tristimulus values to be assigned to the polymer are transformed into a single tristimulus value by means of a filter or a colour limit.

Consequently, the residual tristimulus values correspond to the structure of the cellular metal. In addition, it is also possible to use edge detection techniques (Figure 4), which are mathematically available in the form of the Sobel operator or the Canny algorithm for instance.

The result is a structure matrix whose components may be assigned exactly to either the material structure or the residual structure, and the product of columns and

lines accurately correspond to the pixel number of the scanned image.

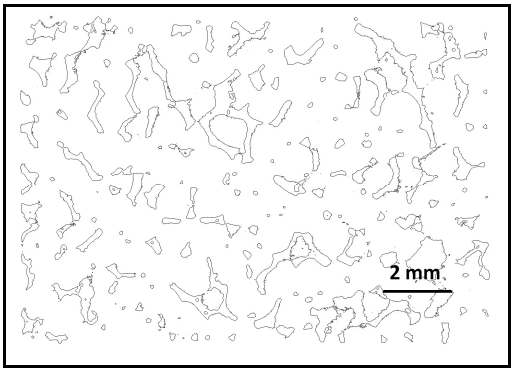

Fig. 4 Binary image after edge detection of Figure 3

3. Modelling of the Surface Profile

To determine a so-called "structure surface profile" - which now only depends on the material structure and corresponds to an ideal measurement by means of a measuring cut - the obtained structure matrix is processed. To do this, a new matrix - the profile matrix - is generated from the structure matrix. The elements of the structure matrix are explored according to their binary value and assigned to the profile matrix according to the result. Figure 5 attempts to elucidate this method.

To determine the profile matrix $\mathbf{P}_{\alpha}$, at point P [1;y_{max}], starting line by line in the direction [x_{max};y_{max}], the matrix element values are analysed. When detecting an element of the material (Point 1) - whose position inside the structure matrix is exactly saved as a position point of the profile matrix - the analysis is continued in x_{max} direction.

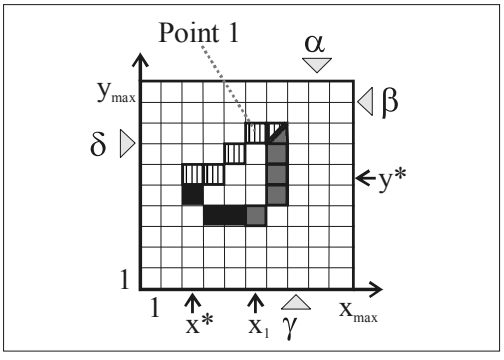

Fig. 5 Section of the structure matrix for analysis

When exploring the next line [y_{max}-n], the column x_1 may be skipped. Consequently, a premature truncation criterion could be applicable for the scan, if all columns of the profile matrix $\mathbf{P}_{\alpha}$ were defined with a material point. Thus the number of lines of a profile matrix changes in contrast to the structure matrix, whereas the number of columns remains constant.

It is also possible to perform the analyses for the directions β, γ, and δ. In the section, additional intersection lines (x* or y*) can be defined and analysed in two directions - thus, for instance, at x* in direction x_{max} or in x=1. As regards Figure 5, the profile matrix $\mathbf{P}_{\alpha}$ would contain the hatched pixels from the α-direction whereas the grey-filled pixel would belong to the β-direction of the profile matrix $\mathbf{P}_{\beta}$.

Consequently, the data stored in the profile matrix **P** corresponds with the surface profile and may be exported (with the assignment of the pixel dimension) as an ASCII data format for further processing.

The following parameters are decisive in obtaining a highly accurate structure surface profile:

- Quality of the sample preparation
- Sample size (the dimensions) which are scanned
- Resolution of the scan system

Accuracy is enhanced as sample size increases, since greater size ensures that it is possible to have at least one material point on each line. Thus, for example, pore width affects the minimal size of the material sample.

4. Evaluation of the Surface Profile

Due to the highly inhomogeneous structure, the application of statistical methods for the evaluation of the surface profile is necessary.

The simplest method is to classify the ordinates of a surface profile into equal sections [6].

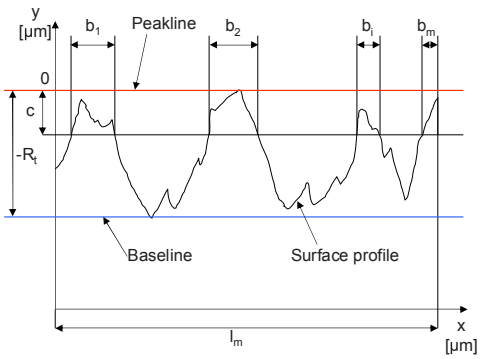

Fig. 6 Scheme of the surface profile nomenclature

A surface profile section P is assumed. This consists of a discrete number of measuring points which are recorded during the modelling of the surface profile in the profile matrix. These points are stored with defined dimensions and can be evaluated.

$$n = \frac{\text{Measured length } l_m\,[\mu m]}{\text{Dimension of one pixel}\,[\mu m]} \quad (1)$$

The total number of events (measurement points) n is calculated according to Equation 1.

To create a frequency distribution the following steps (according to Figure 6) are necessary:

1. Define the highest point of the profile as a zero-level peak line.
2. Sort the measurement points of the profile section according to the magnitude (level) of the ordinate.
3. Count the number of events n_i which have the same amount as the ordinate at a reference line in the range m from 0 to R_t (i.e. between peak and baseline). For the reference line of an analysed surface profile the condition is: $0 \geq c \geq -R_t$.

Thus, the amplitude density function as a function of the reference line position c can be shown between peak and baseline as a function of the relative frequency $\frac{n_i}{n}$

A recommended classification can be performed by uniform or non-uniform division of the ordinate values into disjunct groups based on the events of n_i. The resulting class of frequencies can be represented in the form of a histogram for analogue frequency distribution and evaluation.

The function of the material ratio curve M_r - mathematically a cumulative distribution function i.e. a cumulative frequency distribution function - is calculated by the integration of the amplitude density function within the limits of 0 to the position of the reference line c.

At the same time the material ratio curve M_r for a given reference line between the peak and the base line of the profile represents the ratio of the material-filled length b and the measured length l_m.

The material-filled length b can be calculated with

$$b = \sum_{i=1}^{m} b_i \quad (2)$$

and the material ratio M_r with

$$M_r[\%] = \frac{\sum_{i=1}^{m} b_i}{l_m} \quad (3)$$

The application of the material ratio curve was introduced to surface metrology by Abbott and Firestone [7] and has been proven for the assessment of wood surfaces. One reason is the fact that further surface parameters can be obtained by this curve.

In order to do so, Abbott and Firestone proposed a categorisation of the profile section into a part of a peak - a core and valley area. These parameters - like the core roughness R_k, the reduced peak height R_{pk} and the reduced valleys depth R_{vk} - are standardised according to [8].

Further recommended parameters are the mean profile depth at 50% of the material ratio as well as the maximum profile depth with a material ratio of 100%.

5. Modification of the Surface Profile

An extension of the method for creating the surface profiles is necessary if an application of the surface profile is needed.

The comparison with technically measured surfaces is ensured if the measurement conditions conform to the simulation.

A modification of the profile generation regarding a stylus tip is necessary because of the virtual stylus tip geometry shown in Chapter 3: the tip is characterised by an opening angle of 0° and one pixel width by default.

The structural matrix is calculated to a customised profile matrix, taking into account specific stylus tip geometry.

The technical application of classical conical stylus tips for surface roughness with an opening angle of 90° are not suitable for these materials because of the high aspect ratios and dimensions to be measured.

However, thin knife-like edges (which may have an asymmetric aperture angle) are technically suitable.

For the modelling, this can be represented as a beam: the starting point corresponds to a tip radius of the amount of a pixel width and a variable direction, which would have a suitable value between 0° and 90° (Figure 7).

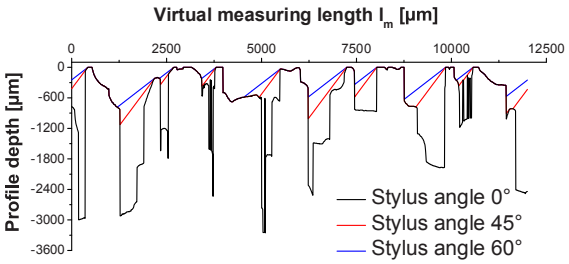

Fig. 7 Surface profiles with different stylus angles of a steel probe with 45 ppi

An opening angle of 45° has been successfully proven, since deeper structures can record more detail.

In addition, the practical implementation of a real knife-like edge as a stylus tip, is ensured.

For this purpose, software has been developed to enable the following aspects of processing the cross sections to be realised:

1. Image processing and filtering
2. The generation of binary image
3. The creation of a virtual surface profile with variable stylus tip geometries
4. The calculation of the function of material ratio

This is sufficient as a base functionality. Further aspects of the software - in terms of calculating the density of material - are given by the ratio between the material points and the corresponding reference area.

The output of the software provides ASCII data of the surface profile and the material ratio curve. Exemplary surface profile and corresponding material ratio curves for analysed open-cell materials with variable pore sizes are shown in Figure 8 and Figure 9 respectively.

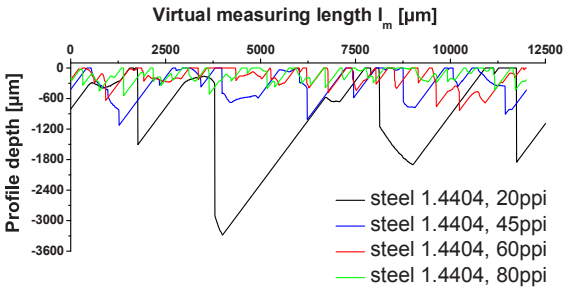

Fig. 8 Surface profiles of different cellular metals with a stylus angle of 45°

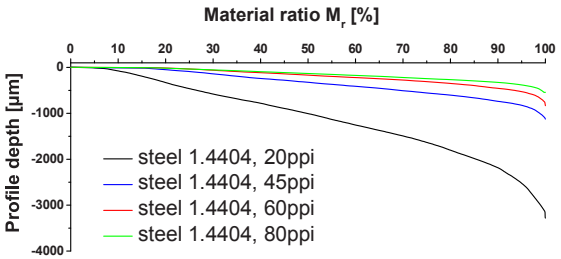

Fig. 9 Material ratio curves of different cellular metals

Table 1 represents the values of the mean profile depth with a material proportion of 50% and the maximum profile depth according to the pore density as well as the pore. These values can serve as surface parameters and can be the basis for comparison with real machined surfaces whilst representing a material immanent value.

Table 1 Parameters of analysed probes of steel 1.4404

Pore density	Pore width [mm]	Mean profile depth [µm]	Maximum profile depth [µm]
20 ppi	2 - 3.5	-1009	-3281
45 ppi	1.1 - 1.3	-324	-1125
60 ppi	0.7 - 0.8	-170	-833
80 ppi	0.4 - 0.5	-134	-542

6. Summary

In this work, a method has been described for the analysis of prepared cross-section images to obtain the surface description of cellular materials based on material structure.

In this way, the necessary condition has been set to enable the practical measurement of cellular materials.

Software developed for the optical image processing of the cross-sections thereby ensures the processing of cross-sectional images, their evaluation and the generation of virtual surface profiles.

The evaluation of the profile sections can be done via the material ratio curve from which parameters – such as the mean profile depth and the maximum profile depth at 50% or 100% - of the material content can be determined.

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